Chapter 8

Structural Health Monitoring of Bolted Joints Using Guided Waves: A Review

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Abstract

Bolted joints are widely applied in engineering structures. Significant advantages of bolted joints are that they can be easily disassembled and the possibility to design for bearing large working load. However, in practical applications, preload loss in pre-tensioned bolts is inevitable. Reliable detection of bolt loosening is significant to ensure structural reliability and safety. In the past decades, the guided wave-based structural health monitoring (SHM) methods have been developed for the detection of bolt loosening, and considerable advancements have been made in this area. This chapter presents a review of the existing studies on bolt preload monitoring method based on guided wave. The basic principle and characteristics of the typical methods are discussed, which involve wave energy dissipation, time reversal guided wave, contact acoustic nonlinearity, and active chaotic ultrasonic excitation-based methods. In addition, this chapter presents an experimental comparison of the detection sensitivity of wave energy dissipation and time reversal method. The results show that the TR method is more sensitive to bolt loosening.

Keywords: bolted joints, bolt-loosening monitoring, structural health monitoring, guided waves, time reversal method

1. Introduction

Bolted joints are widely used in engineering structures such as aerospace and civil structures. Significant advantages of bolted joints are that they can be easily assembled and disassembled and the possibility of bearing large load. In practical applications, bolted joints are subjected to a variety of failure modes including self-loosening, slippage, shaking apart, fatigue cracks, and breaking [1]. Self-loosening is the most common issue among them due to inappropriate preloads during installation, time varying external loads during service, or other environment factors. Bolts loosening may lead to the failure of the entire structure. Therefore, it is critical to monitor bolt preload to ensure the safety and reliability of structures.

Structural health monitoring (SHM) is generally referred to the process of acquiring and analyzing data from on-board sensors to determine the health of a structure [2]. Several SHM approaches have been reported for the detection of bolt loosening in different structural systems, such as vibration, electromechanical impedance, and guided wave-based techniques. In vibration-based techniques, global dynamic properties, like resonant frequencies, modal shapes, and frequency response functions are utilized for the detection of bolt loosening [3]. However, since an assembled structure usually comprises many bolts and joint interfaces which are known as local structural elements, global structural dynamic properties do not change significantly due to bolt preload loosening at a local position [4]. Consequently, vibration-based SHM techniques are relatively insensitive to changes in bolt preloads and thus lead to poor prognostic capability. Impedance-based techniques monitor variations in mechanical impedance due to damage, which is coupled with electrical impedance of piezoelectric transducers (PZTs) [5]. Previous studies have shown the feasibility of using impedance-based approaches for the detection of bolt loosening [6–8]. A piezoelectric transducer (PZT) is attached to a target bolt-jointed structure, and bolt preload can be identified by monitoring the change of the measured electrical impedance [7]. Although this technique is sensitive to minor changes in the bolt preload, its detection area is limited to the near field of the piezoelectric active sensor [9] and an expensive high-precision impedance analyzer with a high-sampling frequency is required [10].

Guided wave-based damage detection techniques have been intensively developed over the last two decades [11, 12]. Due to their sensitivity to small structural damages and large sensing range [13], guided wave techniques have been increasingly used for structural health monitoring. In recent years, bolt preload detection methods using guided wave have received much interest. In this chapter, bolt preload monitoring methods based on guided waves and the relevant theories are reviewed. The objective is to understand the current technology gaps, future research directions, and areas requiring attention of the researchers. This chapter is organized as follows. Section 2 presents the theoretical backgrounds and numerical modeling approach of guided wave-based SHM methods. Then, linear feature-based detection methods are reviewed and compared in Section 3, which include wave energy dissipation methods and time reversal methods. Section 4 displays nonlinear feature-based methods including contact acoustic nonlinearity (CAN), phase shift, and chaotic ultrasonic excitation methods. Finally, conclusions are summarized in Section 5.

2. Theoretical basis and numerical modeling

2.1. Theoretical backgrounds

A typical bolted joint is illustrated in **Figure 1**. It can be seen that a bolted joint usually consists of one bolt, one nut, and two contact parts. From the view of a micro-scale, the joint interface can be considered to be covered with a large amount of asperities. The real contact area is the summation of the contact area of each asperity. As the bolt preload increases, the contact pressure at

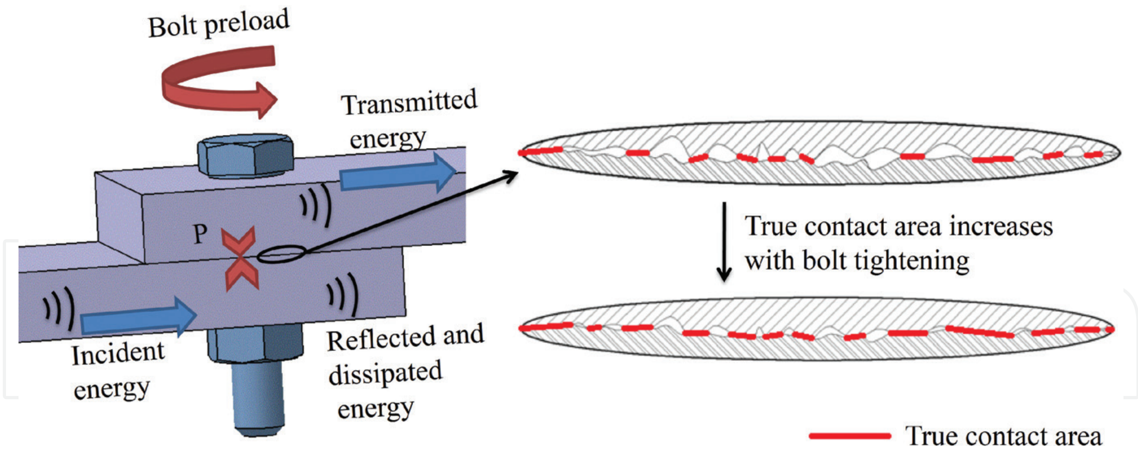

Figure 1. Guided wave transmitted across a bolted joint.

the interface increases. Correspondingly, the real contact area increases as well. When a wave travels through a lap joint, only a part of the incident wave energy can be transmitted, and the other part is reflected and dissipated. Based on Hertz contact theory and the sinusoidal wavy surface model, Yang and Chang [3] establish the relationship between real contact area and contact pressure at a joint interface. Their results show that the energy of transmitted guided wave is proportional to the real contact area of joint interface which increases with bolt preload. Although the topographies of rough contact surfaces are not strictly sinusoidal and the plastic deformation of contact asperities are not considered, Yang's theoretical analysis agrees well with experimental observation. After that, the transmitted wave energy is widely used as the tightness index for bolt-loosening detection. However, based on the theory of rough contact mechanics, the real contact area at an interface reaches a saturation value when the applied contact pressure reaches a certain value [14]. Accordingly, the transmitted energy also saturates when the externally applied load reaches a certain value. In this case, the sensitivity of the transmitted wave energy-based damage detection strategy is reduced considerably.

Nonlinear features of acoustic waves can also be extracted and linked to bolt loosening. Among approaches based on nonlinear features, contact acoustic nonlinearity (CAN) is drawing increasing attention. When the bolt is loosening and the joint is stimulated by acoustic waves or vibration under certain amplitude, joint interface undergoes a certain extent of tension and compression and it opens and closes periodically. This induces asymmetry in the contact restoration forces. Consequently, those forces cause a parametric change of stiffness and lead to structural dynamic nonlinearity, known as contact acoustic nonlinearity [15, 16]. Since the guided wave amplitude excited by a piezoelectric element is generally small, it is difficult to stimulate the nonlinearity of the structure itself. Therefore, impact modulation (IM) and vibro-acoustic modulation (VAM) are two major implementations of CAN-based modulation [17]. The major difference between them is that IM adopts an impact force to excite the natural vibration modes of the inspected structure, while VAM applies a stable vibration to the structure using a harmonic force. The essence of the modulation methods resides on the interaction of the jointed interface with a mixed excitation, like a vibration and a wave. When all the bolts in a jointed structure are fully fastened, the acquired signal spectrum exhibits two peaks at the vibration and wave frequencies, respectively. When bolts are loosening, there would be additional frequency components around the wave frequency in the spectrum, termed as left and right sidebands. The magnitudes of the sidebands, which are determined by the intensity of CAN, can be linked quantitatively to the bolt preload [18].

In order to quantitatively describe the relation between sidebands of signal spectral features and the residual bolt preload, Zhang et al. [18] established a theoretical modeling of CAN in a joint, as shown in **Figure 2a**. The analysis based on the model demonstrates that the magnitude of the sideband is proportional linearly to the nonlinear contact stiffness K_2 which is dependent on the contact pressure at the jointed interface. The above model is a simplified model with single degree of freedom (DOF). Subsequently, Zhang et al. [19] presented a two-DOF nonlinear model to analyze the physical phenomenon of subharmonics and their generation conditions, as shown in **Figure 2b**. On this basis, analytical prediction was carried out to verify the validity of the loosening detection method for bolted joint structures using the subharmonic resonance.

2.2. Numerical modeling

To understand how guided waves interact with bolted lap joints exactly, theoretical models are essential to describe the propagation behavior of guided wave. Apparently, the above simplified single or two DOF models are not enough. Since the bolted structure is inhomogeneous in the direction of wave propagation, it cannot be modeled by analytical or semi-analytical methods. Finite element method (FEM) can be applied to a variety of complex geometries and has become the most common wave propagation analysis method. Therefore, Clayton et al. [20] established a three-dimensional finite element model of guided wave propagation in bolted joints, but interface contact was not considered in order to reduce computational cost. Then, Doyle et al. [21], and Bao and Giurgiutiu [22] used the same method to establish finite element analysis models. However, they found that these models could not reflect the variation of the guided wave under different bolt preloads. Therefore, in order to consider contact

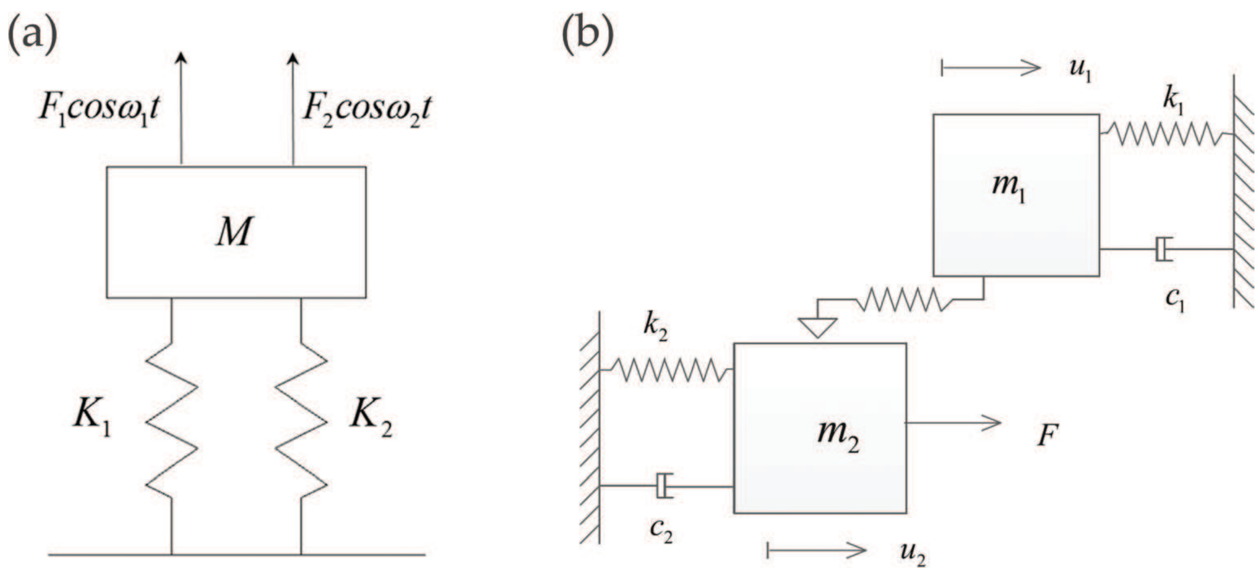

Figure 2. Theoretical modeling of CAN in a joint: (a) single degree of freedom [18] and (b) two degrees of freedom [19].

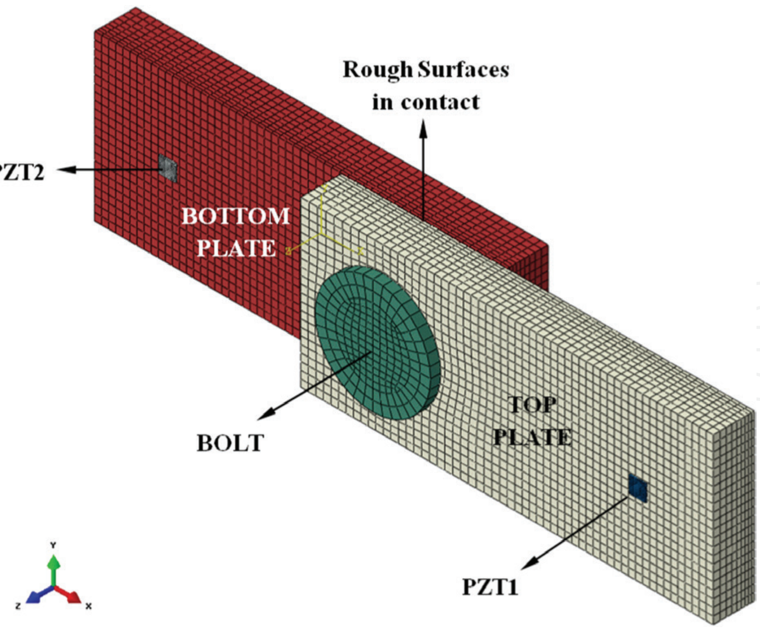

Figure 3. Multi-physics FEM model of bolted lap joint considering rough contact surfaces [10].

behaviors, Bao et al. [23] added contact elements to the finite element model. The improved model can effectively reflect the variation of the guided wave under different preloads, but the wave variations and the measurement results were quite different. The main reason might be that the contact surfaces in the above models are smooth, while the real contact surfaces are rough. In 2016, Parvasi et al. [10] tried to consider rough contact surfaces in finite element model by randomly adjusting node position at the contact surfaces, as shown in **Figure 3**. The simulation results are closer to the experimental measurement results, but the mesh size (1.8 mm) of the contact area is much larger than the size of micro-asperities on rough surfaces.

The above FEM models are mainly used to analyze the relationship between bolt preload and transmitted guided wave energy. Shen et al. [24] built anther 3D multiphysics transient

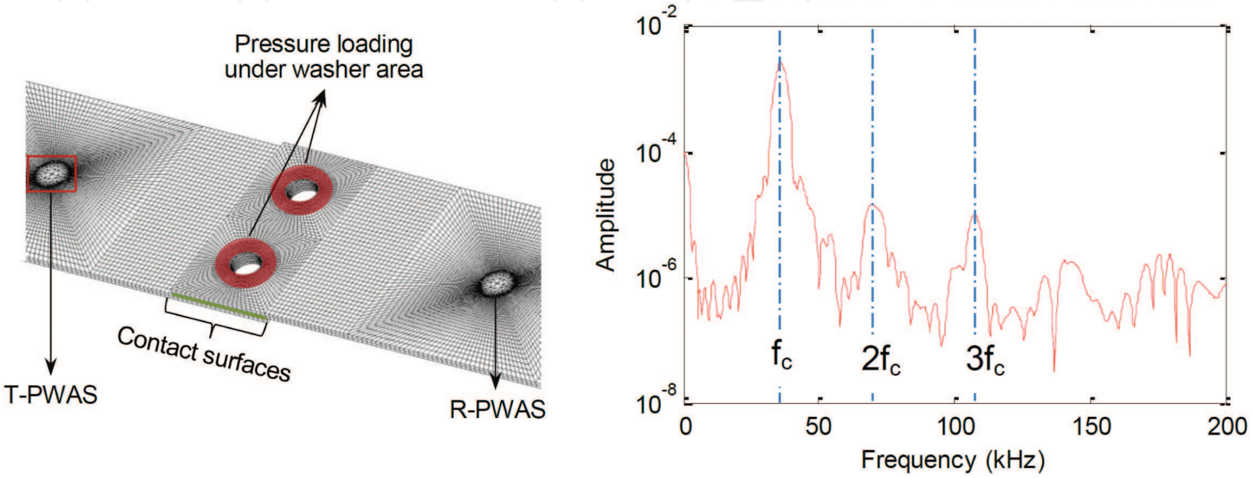

Figure 4. Transient dynamic finite element model and frequency spectrum of simulation signal [24].

dynamic finite element model to analyze the relationship between CAN and bolt load, as shown in **Figure 4a**. The nonlinear higher harmonics (second-order harmonic and third-order harmonic) can be observed clearly in the simulation signal, as shown in **Figure 4b**. The simulation results also displayed that as the bolt preload increases, the ratio of the spectral amplitude at the second harmonic to that at the excitation frequency decreases.

3. Linear feature-based techniques

3.1. Wave energy dissipation

Because ultrasonic wave energy through the bolt joint is strongly tied to the contact status of bolted interface, the transmitted guided wave energy is widely used as tightness index. This type of method is also known as wave energy dissipation (WED) method. In order to detect fastener integrity in thermal protection panels in space vehicles, Yang and Chang [3, 25] used the energy and attenuation speed of guided wave transmitted across jointed interface to assess preload levels and locations of loosening bolt. Subsequently, Wang et al. [26] used only the transmitted guided wave energy to monitor bolt preload. The schematic of the bolt joint monitoring system is displayed in **Figure 5**. The experimental results show that the transmitted energy is basically proportional to torque level. However, the energy does not change with bolt torque when the applied torque reaches a certain value and this is referred to as saturation phenomenon, as shown in **Figure 6a**. Similarly, Amerini and Meo [27] calculated the energy of the transmitted guided wave in frequency domain to assess the tightening state of a bolt lap joint, as shown in **Figure 6b**. Yang et al. [28] extended the WED method to composite bolted joints. With a scanning laser ultrasound system, Haynes et al. [29] acquired the full-field wave data and calculated the wave energy before and after the lap joint to monitor bolt torque levels. Unfortunately, saturation phenomena are also observed in all the above experimental studies. On the other hand, due to multi-mode, dispersion, and boundary reflection of guided waves, the response signal at a joint structure is quite complex [27]. Hence, Kędra et al. [30] investigated the effects of excitation frequency, the time range of received signal, and the position of sensor on the preload detection accuracy of the WED method. They pointed out that these parameters have to be carefully selected.

The above bolt preload detection methods are limited to a flat lap joint with a single bolt. However, in real structures, bolted joints with complex geometry or multiple bolts are more common. In this case, complex signal-processing methods are always needed. In order to

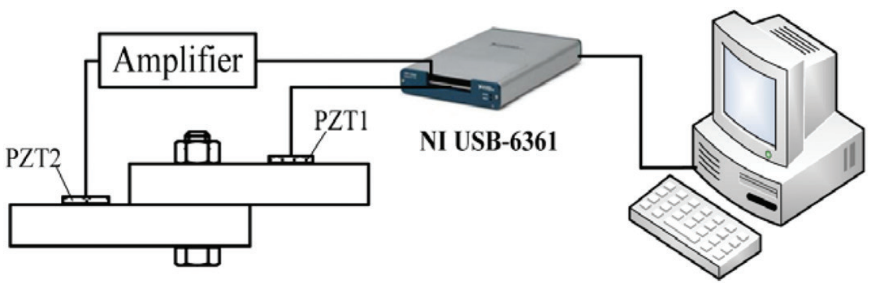

Figure 5. Schematic of the bolt joint monitoring system [26].

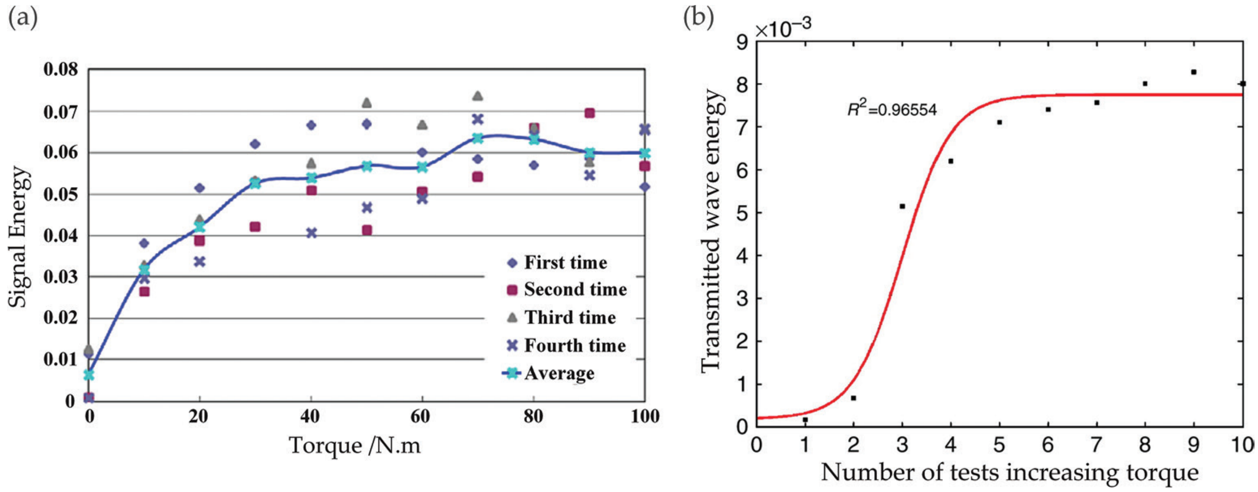

Figure 6. Results of WED methods with saturation phenomenon: (a) result from reference [26] and (b) result from reference [27].

monitor the preload of L-shaped bolt joints, Jalalpour et al. [31] proposed a preload monitoring method using fast Fourier transform, cross-correlation, and fuzzy pattern recognition to process transmitted wave. Nevertheless, the fuzzy sets of torque level were limited. Montoya et al. [32] assessed the rigidity of L-shaped bolt joint using transmitted wave energy. Subsequently, Montoya et al. [33] further extended the method to bolt loosening and preload monitoring of satellite panels jointed by a right angle bracket. Their experimental results display that some measurement parameters, such as the time window of the received signal, have a significant effect on the sensitivity and repeatability of the measurement [33]. With respect to bolt-loosening monitoring in multi-bolt-jointed structures, Mita et al. [34] proposed to use support vector machine to recognize different loosening patterns. Their results show that the proposed method could identify the location and the level of preload of loosened bolts. Moreover, Liang and Yuan [35] developed a decision fusion system for multi-bolt structure, as shown in **Figure 7**. This system consists of individual classification, classifier selection, and decision fusion. The results demonstrate that the proposed method can accurately and rapidly identify the bolt loosening by analyzing the acquired wave signal.

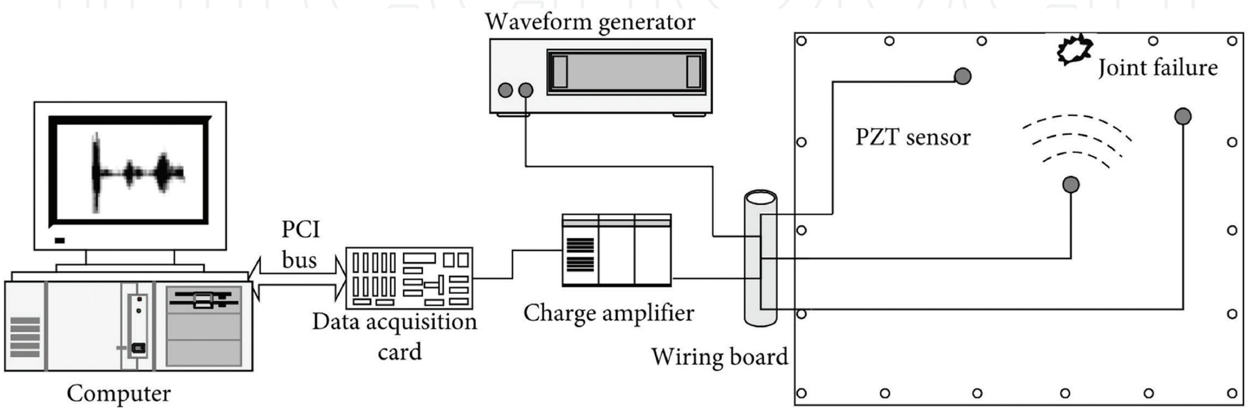

Figure 7. Sensor layout and joint failure position on the specimen [35].

3.2. Time reversal method

Since guided wave signals are always very complex because of multi-mode, dispersion, and scattering at any discontinuity, Fink et al. [36] extended time reversal concept (TR) to a guided wave monitoring technique. In time reversal approach, a received signal is reversed and reemitted as an excitation signal, and then a reconstruction of the input signal can be obtained at the source position. Hence, the time reversal method can effectively reduce the influences of dispersion and multi-modal of the guided wave. In recent years, time reversal-based guided wave monitoring methods have been widely applied to damage detection in various structures, such as metallic plates [37], composite plates [38–40], and rebar-reinforced concrete beams [41]. Recently, Parvasi et al. [10] proposed to use time reversal method to focus guided wave energy transmitted through bolted joint, and then the refocused amplitude peak was selected as the tightness index for preload detection. The experimental results show that the proposed tightness index increases with bolt torque. The TR method for bolt preload monitoring can be divided into four steps, which is shown in **Figure 8**. Step 1, a tone burst input e(t) is applied to transducer A, which activates wave propagation in the plate. Step 2, a wave response signal u(t) is captured by transducer B. Step 3, the recorded signal u(t) is reversed in time domain and is restimulated using transducer B. Step 4, a guided wave signal is captured by transducer A again, and the original signal is reconstructed. Finally, the reconstructed signal peak is used as the tightness index for preload detection [10]. One of the main advantages of TR method is that there is no need to take efforts to select time window of received signal as the WED method.

Actually, the refocused amplitude peak is strongly related to the transmitted wave energy. Hence, when bolt preload is relatively high and the real contact area does not increase with preload, the focused signal peak amplitude changes very slowly. Therefore, Tao et al. [42] experimentally investigated the saturation phenomenon of TR method for bolted preload detection. The results demonstrate that with the increase of the surface roughness of bolted

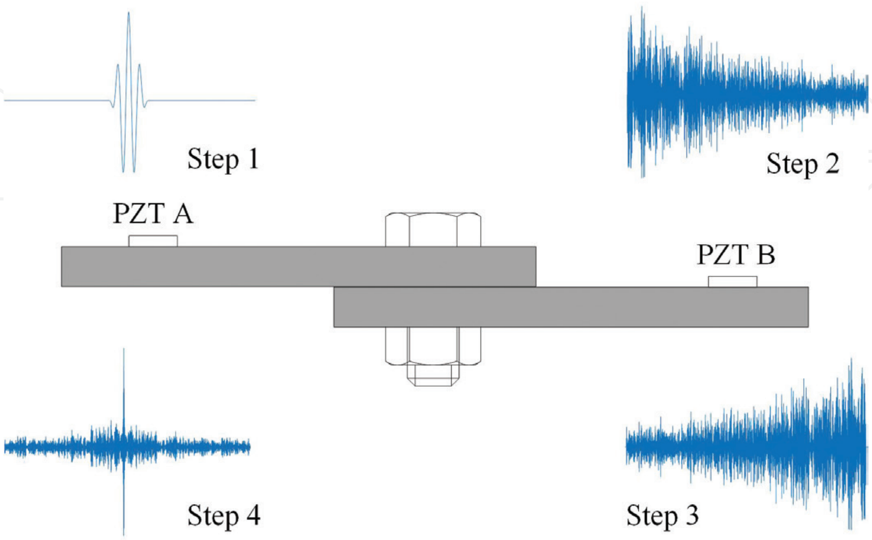

Figure 8. Illustration of the time reversal method in a lap jointed beam.

interface, the saturation phenomenon becomes insignificant. Huo et al. [43] studied guided wave propagation across contact interface based on fractal contact theory and finite element method. They concluded that the saturation phenomenon is linked to the plastic deformation of interacting asperities under a heavy axial load.

3.3. Comparison of TR and WED methods

Until now, the difference in monitoring sensitivities of WED and TR methods is not clear. Hence, the monitoring sensitivities of the two methods are compared in this section. The experimental setup and specimens are displayed in **Figure 9**. The metallic bolted lap joint consists of two flat aluminum 2024-T3 beams, one M6 bolt, one nut, and two washers. The length of each beam is 400 mm, the width is 50 mm, and the thickness 2 mm. The normal torque is selected to be 10 Nm. A torque wrench with a resolution of 0.2 Nm is used to apply bolt preload. A data acquisition (DAQ) system NI USB-6366 with a sampling frequency of 2 MHz is used to generate wave excitation and record responses. A program is built in the LabVIEW environment to control the process of data acquisition. A high voltage amplifier PINTEK HA-400 is used to amplify the excitation signal and provides voltage to PZT actuators. In addition, the specimen is mounted on a foam support to simulate a free-free boundary condition. Two PZT patches are bonded on the specimen. The patch on the left beam, 100 mm, away from the bolt is numbered as PZT 1 PZT. Another one on the right beam, 100 mm, from the jointed bolt is numbered as PZT 2.

The bolt preload is evaluated by both WED and TR methods at the same time. **Figure 10** presents the results of tightness indexes TI_{Ω}(WED) and TI_{Ω}(TR) obtained by $TI_{\Omega}(WED)$, the WED and TR methods, respectively. $TI_{\Omega}(TR)$ It can be seen that TI_{Ω}(WED) increases with bolt preload when the preload is smaller than 6 Nm. However, an obvious saturation trend can be seen, and only the lowest 0.1-Nm torque case can be clearly identified. By contrast, TI_{Ω}(TR) increases with bolt preload in the entire preload range, and the 0.1-, 2-, and 4-Nm cases can be clearly identified. On the other hand, TI_{Ω}(TR) cannot be used to identify torque cases larger than 6 Nm. It can be concluded that the detection sensitivity of TR $TI_p(MTR)$ method is better than that of $TI_{\Omega}(WED)$ WED method $TI_{\Omega}(TR)$ especially at the early stage of bolt loosening. The

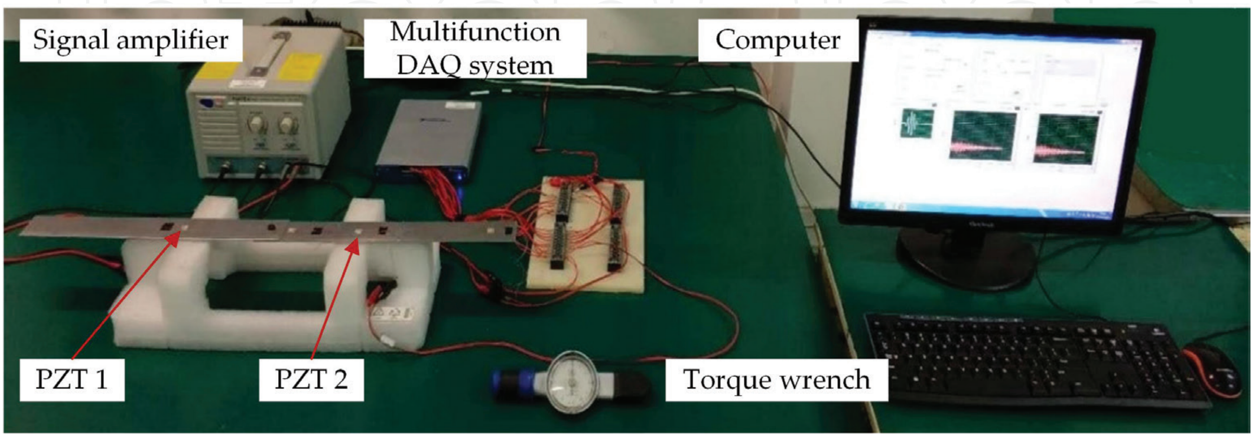

Figure 9. Experimental setup and specimens.

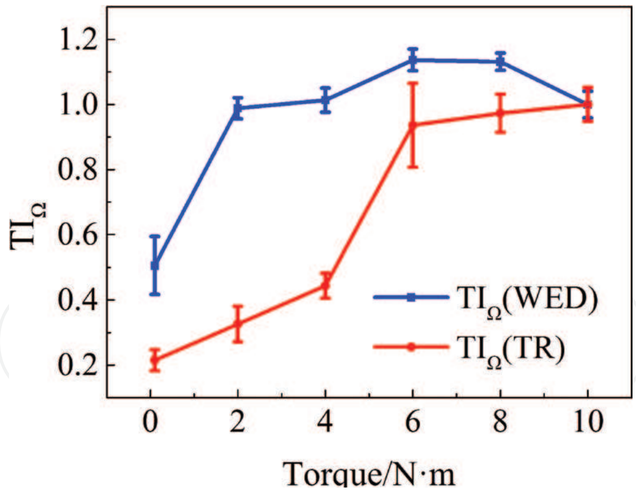

Figure 10. Preload detection results of the WED and TR methods.

main reason is that guided waves traveled twice (from PZT1 to PZT2, and then PZT2 to PZT1) through the jointed interface in the TR technique. The interface affects the waves twice and thus makes the TI_Ω(TR) more sensitive to the bolt preload [10].

4. Nonlinear feature-based techniques

4.1. Contact acoustic nonlinearity

Contact acoustic nonlinearity (CAN) is shown to increase with the decrease in contact load, so the second-order harmonics, subharmonic, and spectral sidebands caused by CAN have also been used for bolt preload detection. Usually, the second-order harmonic and subharmonic can be generated by a single frequency excitation, and spectral sidebands are generated by both low- and high-frequency excitations. For the second-order harmonic-based method, the ratio between the second harmonic amplitude and the carrier frequency signal amplitude provided a reliable index for bolt load assessment. Under multi-frequency excitation, the loosening/tightening index proposed is the difference in dB between the carrier frequency amplitude and a mean of the two sideband amplitudes [27]. Zhang M et al. [19] presented a subharmonic resonance method for the detection of bolt looseness, and the bolted joint was excited by a single frequency-guided wave. CAN features are more likely to be excited by adding vibration excitation. Thereby, Zhang Z et al. [17, 18] proposed a vibro-acoustic modulation (VAM)-based method and developed a sideband index for metal and composite bolted joints. The experimental setup and the corresponding detection results for composite bolted joints are shown in **Figure 11**.

In **Figure 11**, the label β is the sideband index in VAM method, and the label energy is the transmitted energy of Lamb waves in WED method. Zhang Z et al. [17] compared the proposed VAM method with WED-based linear method, and the results show that the proposed sideband index β effectively enhanced measurement sensitivity. In addition, Amerini and Meo [27] developed

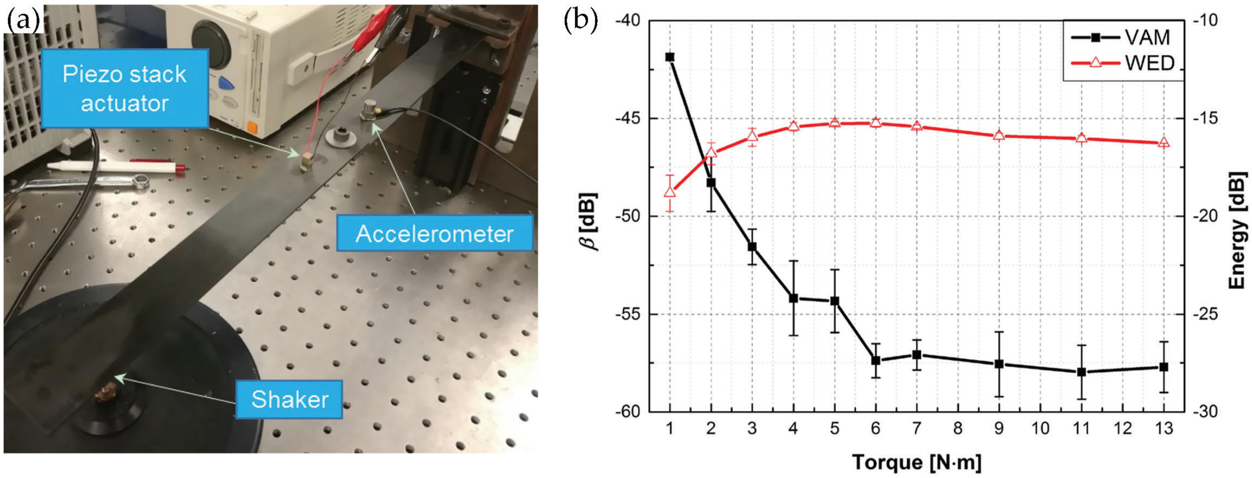

Figure 11. Preload monitoring of bolted composite joint using VAM method [17]: (a) experimental setup for VAM method and (b) comparison of VAM and WED methods.

both second-order harmonics index and sideband index to assess the tightening state of a bolted structure, and the assessment results of the two methods are similar. On the other hand, Zhang Z et al. [16] also compared the high-order harmonics and sideband methods and demonstrated that the stability of spectral sideband-based method is better. Spectral sideband can also be generated by impact modulation. Meyer and Adams [44] proposed an impact modulation-based method to detect bolt loosening in an aluminum joint. However, the sideband amplitudes are sensitive to test parameters including impact amplitude and location, probing force amplitude and frequency, and sensor location. One common disadvantage of these above spectral sideband methods is that it needs two different actuators and one sensor for each joint monitored [27]. Meanwhile, the saturation phenomena have not been completely removed, and the detection sensitivity still needs to be improved at the early stage of bolt loosening.

4.2. Phase shift

Apart from transmitted wave energy and CAN, the phase shift of guided wave has also been used for quantifying bolt torques. Zagrai et al. [45] estimated bolt torques by measuring delays of guided wave transmitted across bolt joint. Their experimental results demonstrated that bolt torque is proportional to phase shift of the guided waves, as shown in **Figure 12**.

In addition, Zagrai et al. [45] tried to explain the experiment results by acousto-elastic theory and presented a simplified theoretical approach to calculate phase shift of the propagating elastic wave. However, their approach gives approximately an order of magnitude underestimation for pulse delays. Subsequently, Doyle et al. [46, 47] further studied phase shift of guided wave propagating in a complex structure analogous to a typical satellite panel containing 49 bolt joints using an array of piezoelectric sensors sparsely distributed. The results show that the time at which this shift occurs is related to the distance between the location of loosening bolt and the primary wave propagation path. Thereby, using only two or three possible paths, it is possible to obtain a realistic estimate of the location of damage in the form of single bolt loosening [47]. On this basis, Zagrai et al. [48] tried to develop a baseline-free method utilizing

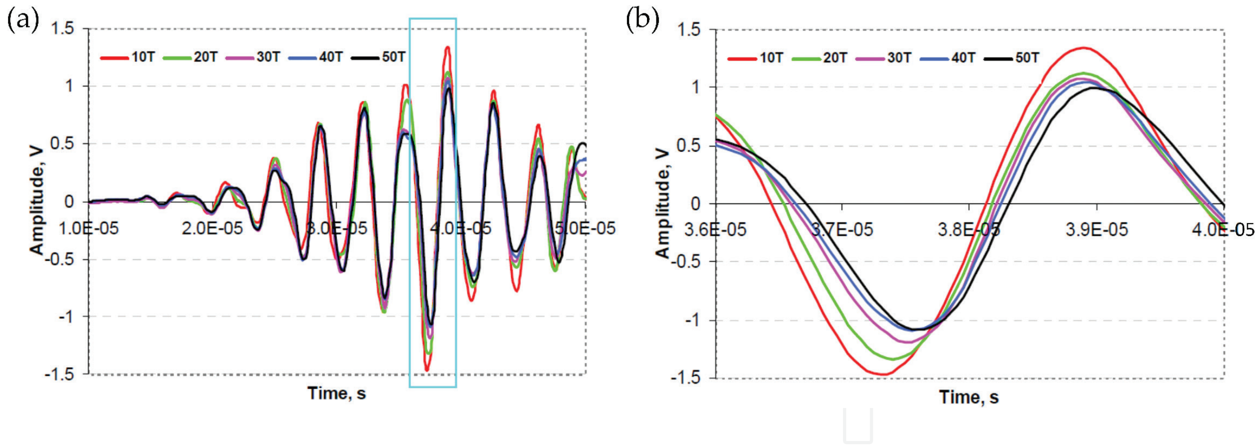

Figure 12. Guided wave signals recorded at different bolt torques: (a) full records and (b) zoomed-in segments [45].

signals of different initial phases to assess bolt loosening. Unfortunately, it does not work in structures with complicated geometries and large number of bolts. Furthermore, changes of the phase shift induced by a bolted joint are rather small and require sensitive equipment with advanced signal-processing capabilities [46]. In addition, because received guided waves are very complex, it is difficult to select the correct time window and the corresponding wave speed to calculate phase shift and the distance between wave path and damage.

4.3. Chaotic ultrasonic excitation

In addition to stimulate the nonlinear characteristics of the jointed structure, another research idea is to directly use nonlinear ultrasonic excitation. At this time, artificially introducing a nonlinear component in the ultrasonic excitation signal can be used to sensitively estimate the change of structural parameters caused by loosened bolts. Chaotic signal is a well-known nonlinear signal, but chaotic signals generated by most well-known chaotic systems are unsuitable for guided wave monitoring which is more sensitive to small-scale damage.

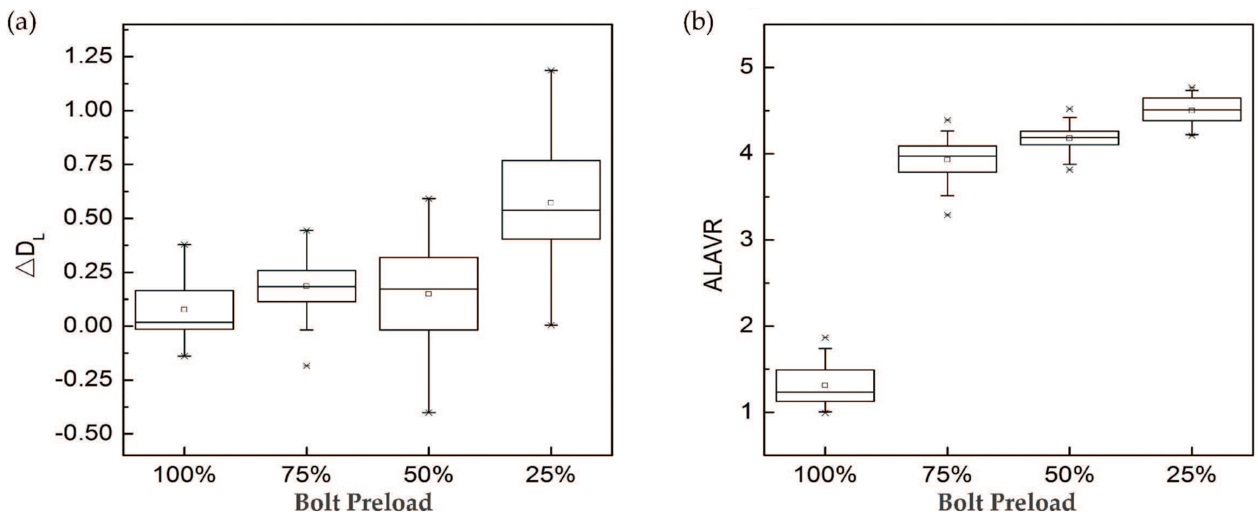

Figure 13. Looseness indexes versus bolt preload [51]: (a) Lyapunov dimension and (b) ALAVR.

Clayton et al. [20] proposed a bolt preload monitoring approach combining a chaotic excitation method with ultrasonic guided waves. In this method, the chaotic signal is upconverting to an ultrasonic frequency band, and the ultrasound signal with chaotic characteristics is generated to stimulate the bolted structure. The response signal is reconstructed to analyze the phase space, and the nonlinear characteristic quantitatively representing the bolt looseness is extracted. Fasel et al. [49, 50] used similar methods to identify bolt preload in simulations and experiments on single and multi-bolt structures. Recently, based on the chaotic ultrasonic excitation method, Wu and Xu [51] take both Lyapunov dimension and the ratio of averaged local attractor variance (ALAVR) as looseness indexes, which can be used to characterize an attractor's whole features and local features. Experimental results show that ALAVR is better for bolt preload monitoring, as displayed in **Figure 13**.

5. Conclusions

Ultrasonic guided wave is an effective technique to monitor the preload of bolts. The research status of this field is reviewed in this chapter. At present, considerable advancements have been made in this area in the past two decades. Both linear and nonlinear features of guided waves introduced by bolted joints have been used for bolt preload monitoring. In particular, the transmitted wave energy as a linear feature is the most extensively used for preload monitoring in single bolt and multi-bolt structures. For this reason, the wave energy dissipation method (WED) based on the above features is experimentally compared with time reversal method (TR). The results show that the detection sensitivity of WED method is not very good, especially at the early stage of bolt loosening, and the TR method is more sensitive to bolt loosening. Meanwhile, this chapter also reviews a variety of monitoring methods based on nonlinear features, including contact acoustic nonlinearity (CAN), phase shift caused by acoustic-elastic, and chaotic ultrasound. The above methods can improve the detection sensitivity, but there are also several disadvantages. For example, both acoustic and vibrational excitations are always required for CAN-based methods, and high-frequency sampling frequencies are required for phase shift-based method. The open areas of research, which might need attention, are outlined as follows:

1. Accurate and efficient numerical models should be further developed to simulate wave propagation in bolted joints. For example, acoustic-elastic are currently believed to cause the phase shift of transmitted guided-wave signal. However, the current simplified model based on acoustic-elastic cannot effectively explain the phase shift phenomenon. In the meantime, it is very difficult to consider the micro-topography of contact surfaces in FEM models now. Therefore, the establishment of a more accurate and efficient numerical model is expected to fully study the interaction between jointed interface and guided wave theoretically.

2. Improving bolt preload monitoring method is still required. Although bolt preload monitoring methods such as TR and VAM methods can effectively improve the preload detection sensitivity, the detection sensitivity of these methods is not still very good at the early stage of bolt loosening. Moreover, almost all the methods currently require baseline

signals from healthy structures. Therefore, the establishment of a baseline free monitoring method with a high detection sensitivity is an important step for moving toward the goal of real-life in-service implementation.

3. Bolt-loosening detection methods considering environmental factors for multi-bolt structures should be further developed. Current research limited to a flat lap joint with a single bolt. However, bolted joints with complex structure and multiple bolts are more common in real structures. Meanwhile, little attention has been paid to preload monitoring considering environmental factors which have significant effect on guided wave monitoring. Hence, loosening detection method considering environmental factors for multi-bolt structures is also very important for realizing the application of bolt preload monitoring in real engineering structures.

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Nomenclature

ALAVR	ratio of averaged local attractor variance
CAN	contact acoustic nonlinearity
DOF	degree of freedom
FEM	finite element method
IM	impact modulation
K_1, K_2	contact stiffness
PZT	piezoelectric transducers
SHM	structural health monitoring
TR	time reversal
TI_Ω	tightness index
VAM	vibro-acoustic modulation
WED	wave energy dissipation
β	sideband index
ΔD	tightness index based on Lyapunov dimension

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